

Status, Results, and Plans for Development of GPS Buoys: Potential for SWOT In-situ CALVAL

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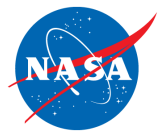
GPS Buoy Project

- Joint NASA JPL, NOAA PMEL and U. Washington project funded through NASA ROSES call (Physical Oceanography)*

OBJECTIVES:

- Design, build and test a modular, low-power, robust, high-accuracy GNSS measurement system for long-term, continuous and autonomous operations on ocean- and cryosphere-observing platforms.
- Probe the limits of new kinematic precise-point positioning (PPP) techniques for accurately determining sea-surface height, and recovering neutral and charged atmosphere characteristics.
- Explore potential scientific benefits—in the fields of physical oceanography, weather and space weather—of accurate GNSS observations from a global ocean network of floating platforms.

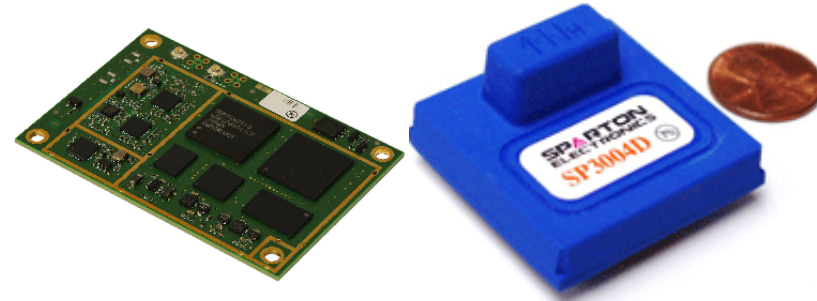
**Extending the Reach of the Global GNSS Network to the World's Oceans: A Prototype Buoy for Monitoring Sea Surface Height, Troposphere and Space Weather, B. Haines, S. Brown, S. Desai, A. Komjathy, R. Kwok, D. Stowers, C. Meinig and J. Morison.*



Prototype Precision GPS Bouy

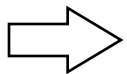
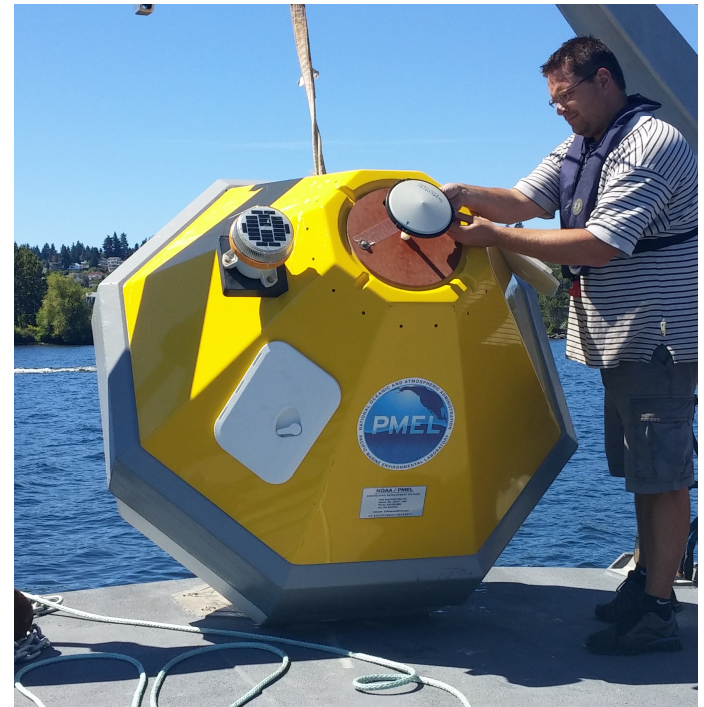
FEATURES

- Integrated low-power (~ 1 W), dual-frequency GPS system (Septentrio)
- Miniaturized digital compass/accelerometer.
- Iridium communications.
- Adaptable to multiple floating platforms (e.g., buoy; wave gliders).
- Enables geodetic quality solutions without nearby reference stations.



DEVELOPMENT AND TESTING

- Buoy tested successfully under progressively more challenging conditions:
 - ✓ *Lake Washington (Aug. 7–12, 2015).*
 - ✓ *Puget Sound (Nov. 10 to Dec. 14, 2015).*
 - ✓ *Daisy Bank: open ocean Jason crossover location (May 11 to Sep. 8, 2016).*
 - ✓ *Monterey Bay: SWOT Pilot Experiment (June 22 to September 7, 2017).*

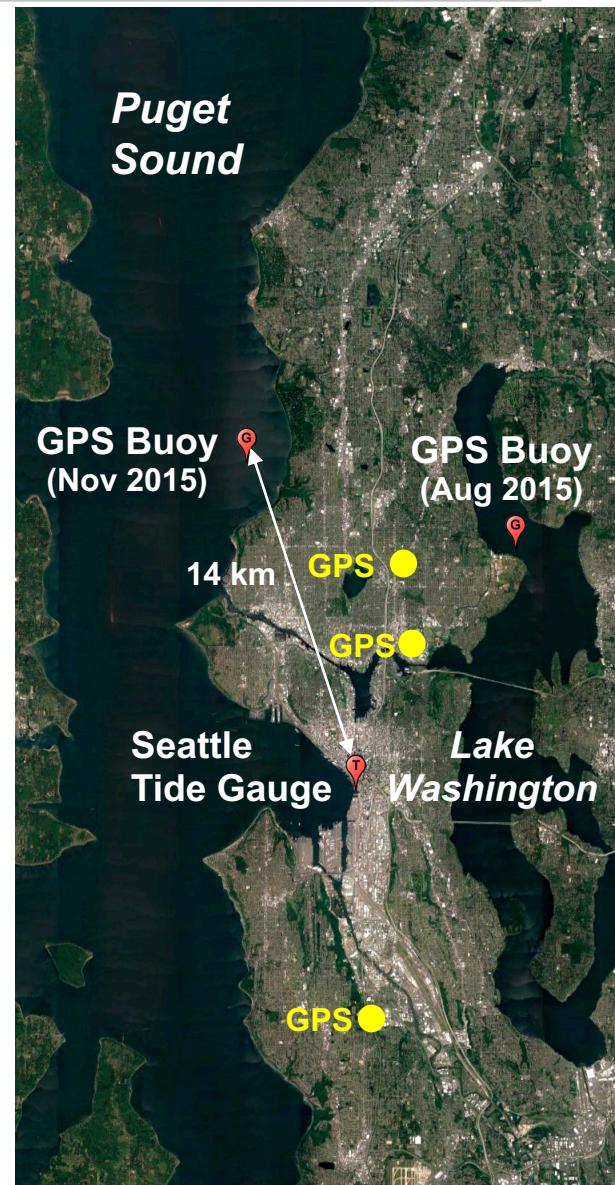


Total of 236 days in the water (20 days of data from Monterey Bay data lost due to failed USB drive).



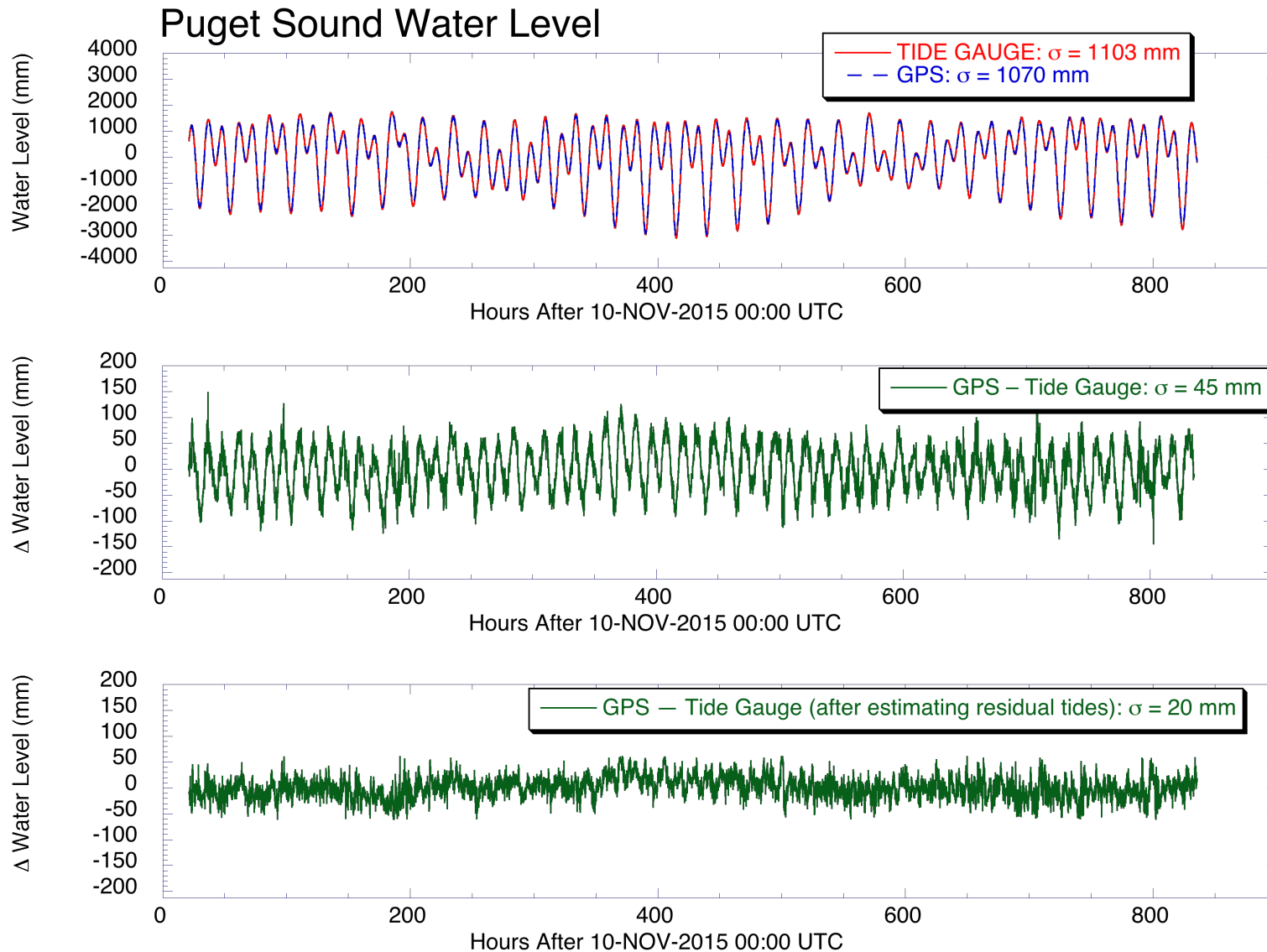
Lake Washington and Puget Sound: Early (2015) Campaigns

- First open water tests (5 days) in Lake Washington
 - Shallow mooring in freshwater lake: no ocean tides.
 - Provided test of new precise point positioning (PPP) approach: 1–2-cm repeatability in lake level (30-min averages).
 - Showed systematic 3-cm drop in water level, consistent with lake-level gauge at ship canal lock.
 - Demonstrated ability to accurately recover zenith troposphere (< 1 cm accuracy).
 - Revealed small wind waves linked to diurnal wind patterns.
- Month-long test in Puget Sound
 - Shallow water (~ 170 -m) mooring in inland saltwater sea.
 - Typical SWH of ~ 0.5 m.
 - Strong ocean tide signal: mean tidal range of 2.3 m.
 - 14 km “as the crow flies” from Seattle tide gauge (across West Point in Elliott Bay).





GPS vs. Tide Gauge: Puget Sound



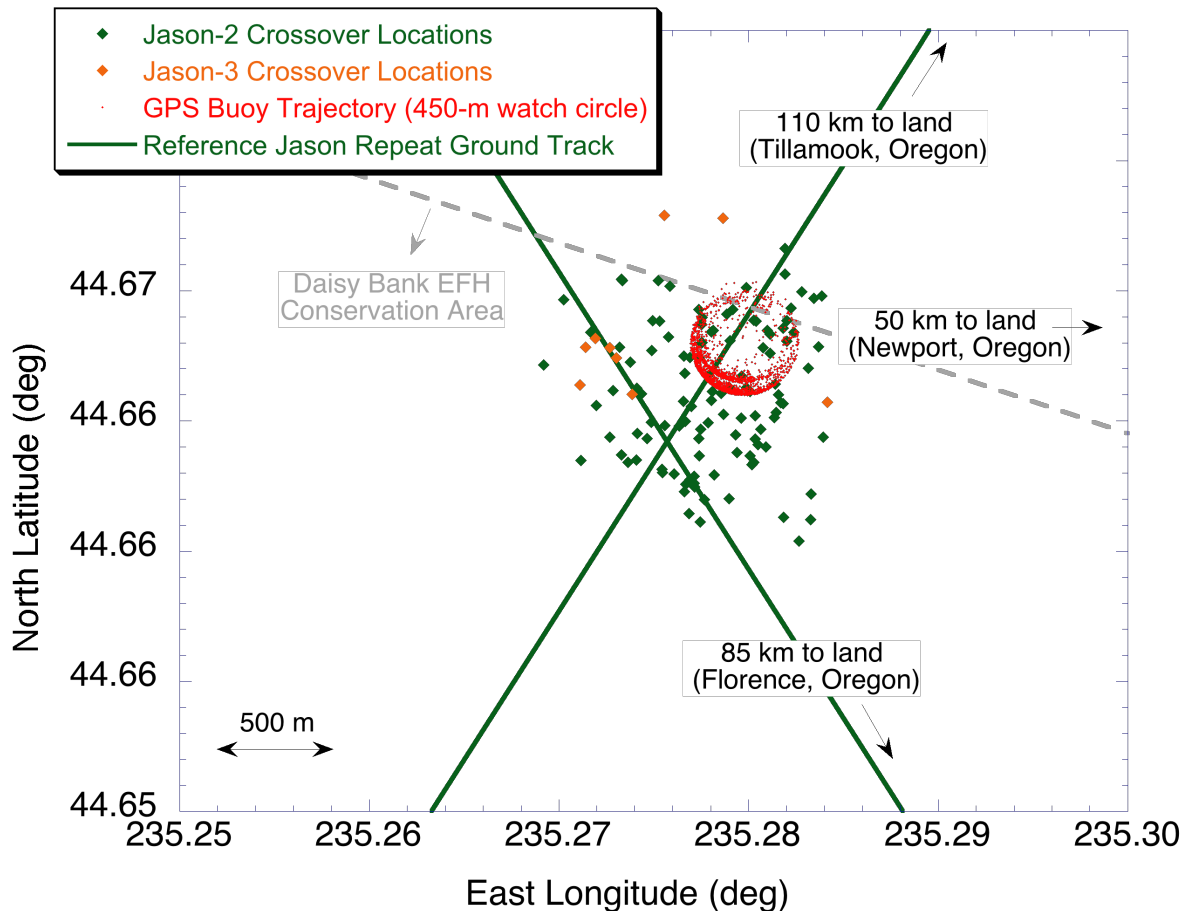
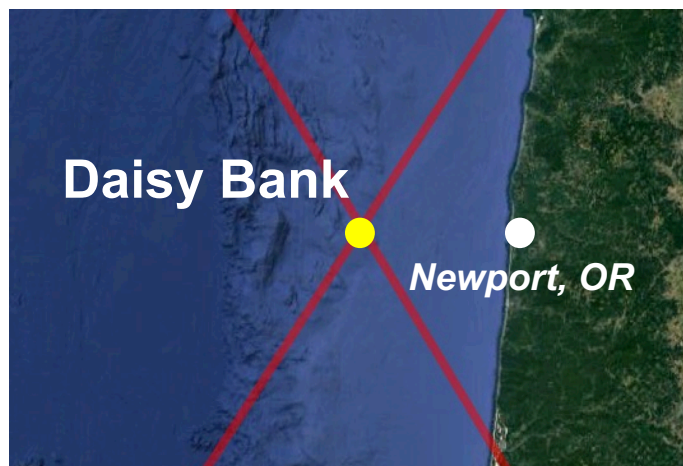


Daisy Bank (2016)

First Open Ocean Campaign

Daisy Bank

- Summer 2016 GPS Buoy Campaign at Jason Crossover Location
- Buoy moored 50 km offshore over submarine rock outcrop (shallow water).
- Typical SWH of 1–3 m.
- Operated continuously for 120 days (May thru Sep).
- Deployment spanned 24 dual Jason 2/3 overflights.



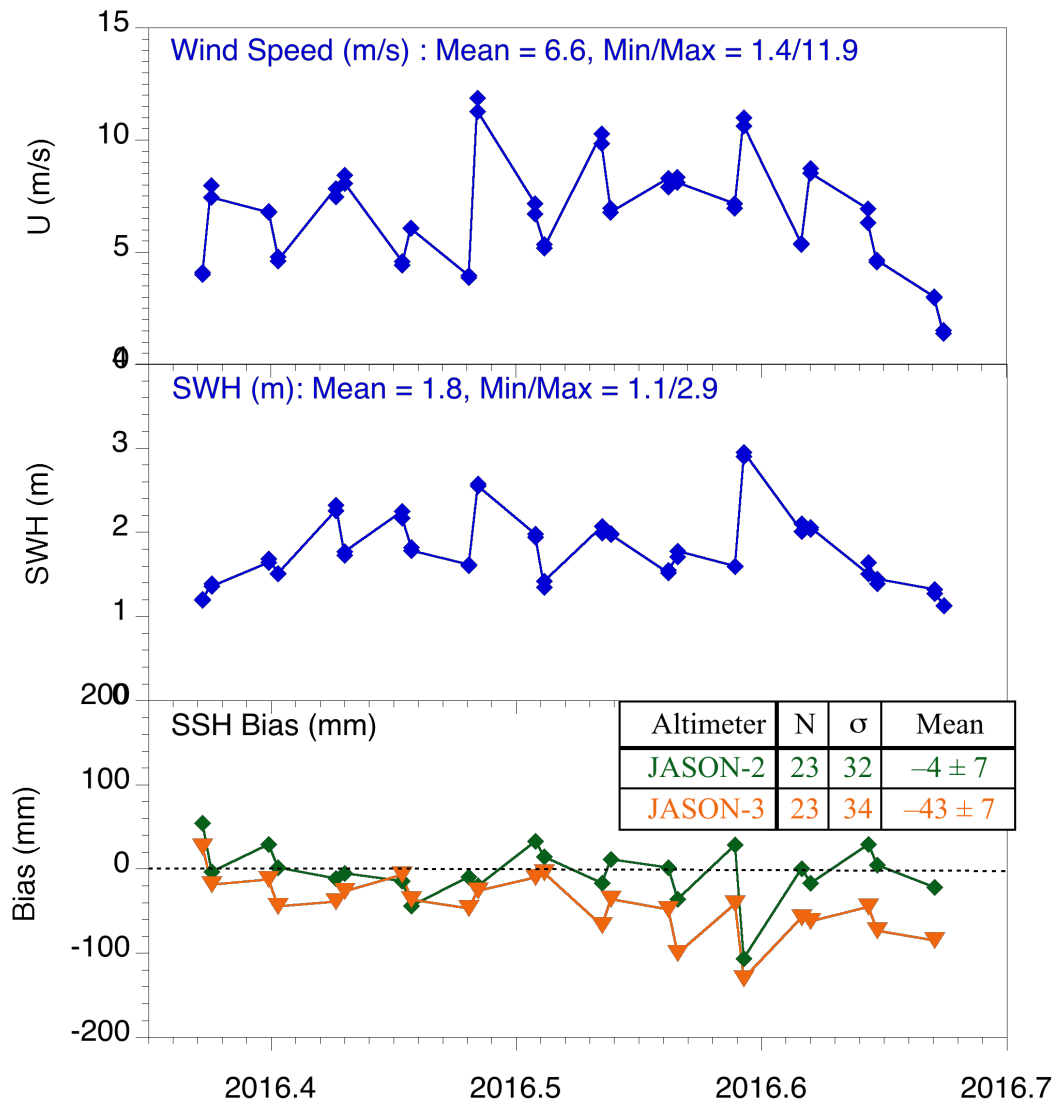
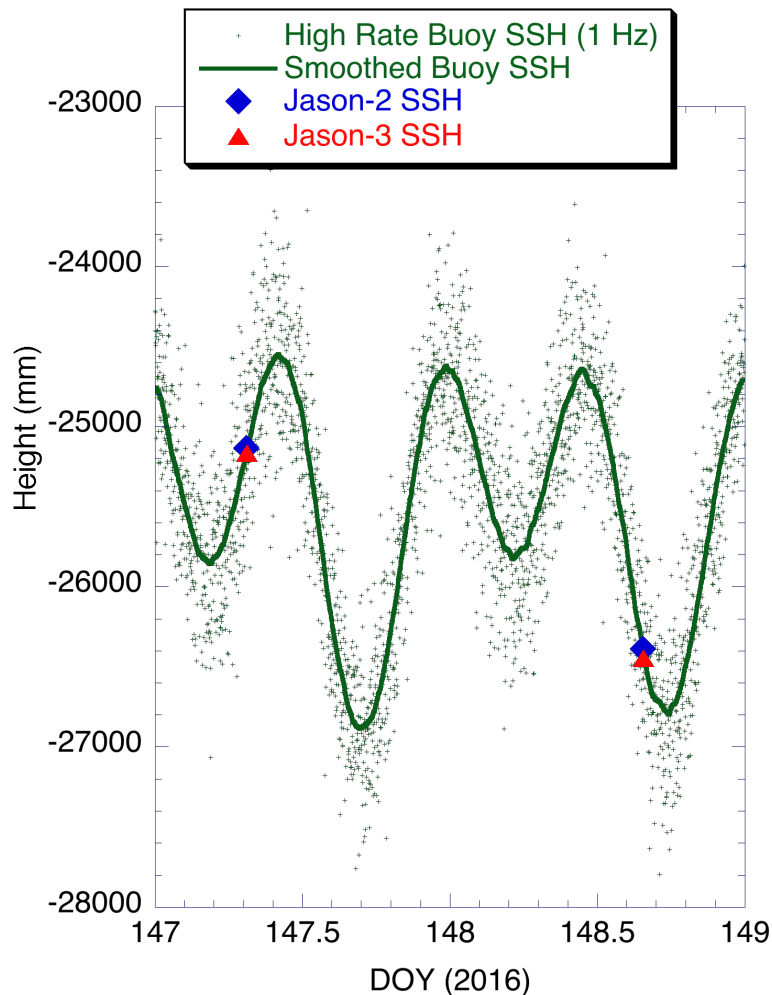
DAISY BANK CLOSEUP
~200-m depth



Daisy Bank (2016)

Comparison to Jason Sea Surface Height

Buoy vs. Altimeter SSH: May 26–27, 2016

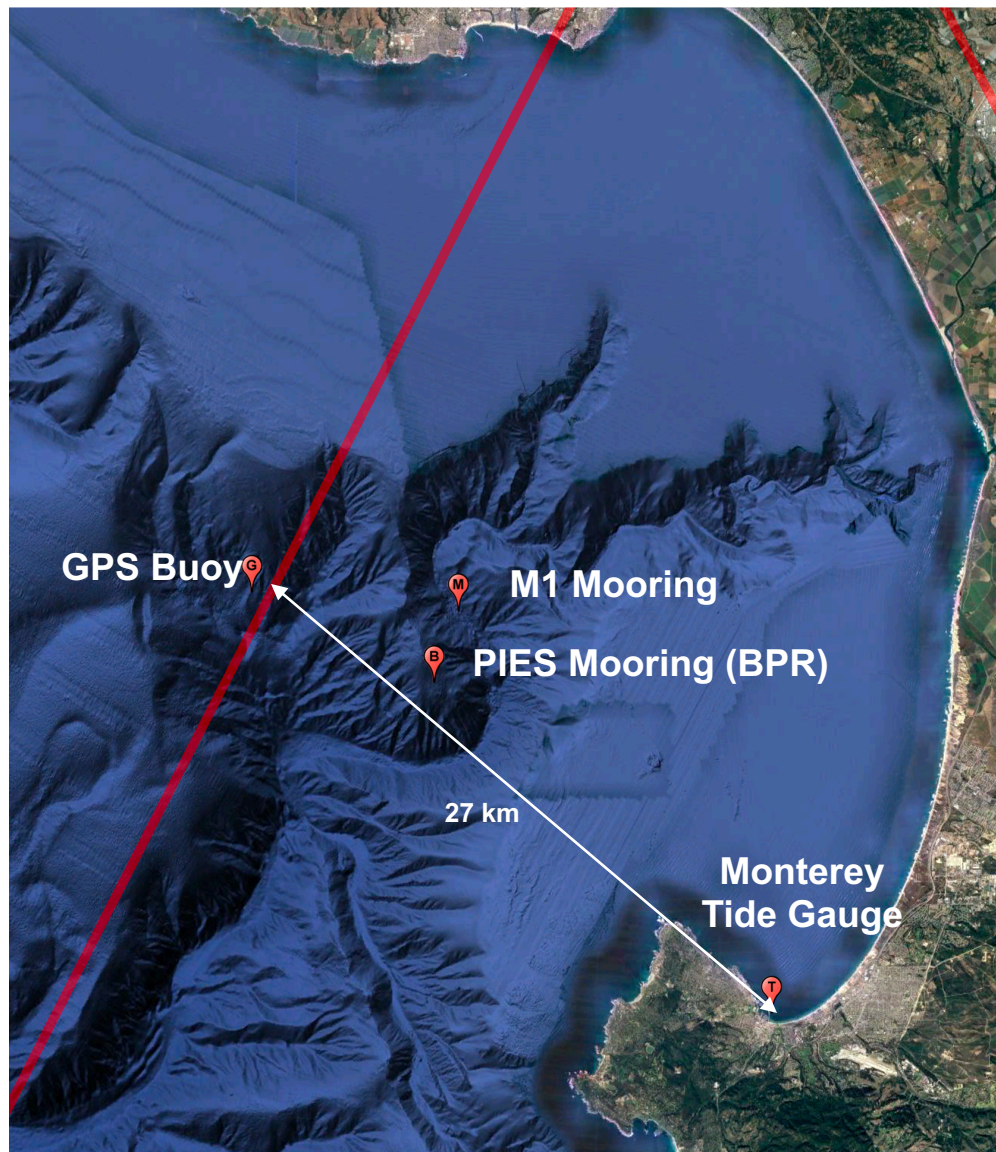




Monterey Bay (2017): SWOT Pilot Experiment

Monterey Bay

- Summer 2017 GPS Buoy deployment to complement SWOT glider campaign.
- Buoy moored 20 km offshore over steep wall of Monterey Canyon.
- Mooring depth of ~1000 m, with watch circle diameter of ~2 km
- Operated continuously for ~60 days (after repair of failed USB drive).
- Adjacent to ascending Jason track.
- Deployment spanned 6 Jason-3 overflights.



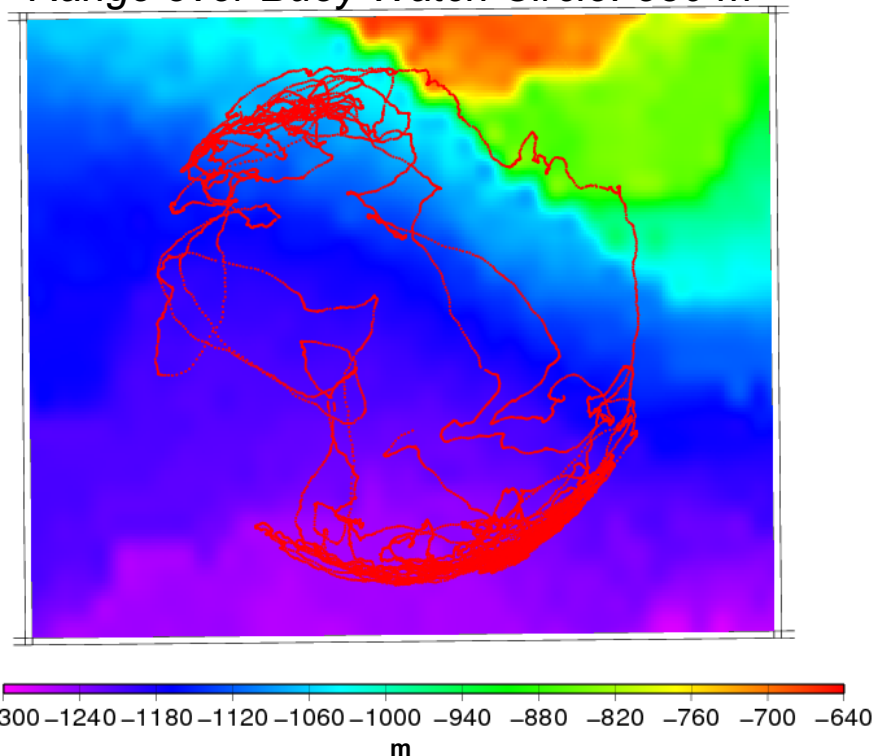


Monterey Buoy Results Underscore Importance of Geoid Signal

In Monterey Experiment, buoy was moored in ~1000 m of water over the steep walls of Monterey Canyon, the largest submarine canyon along the west coast of North America.

Bathymetry

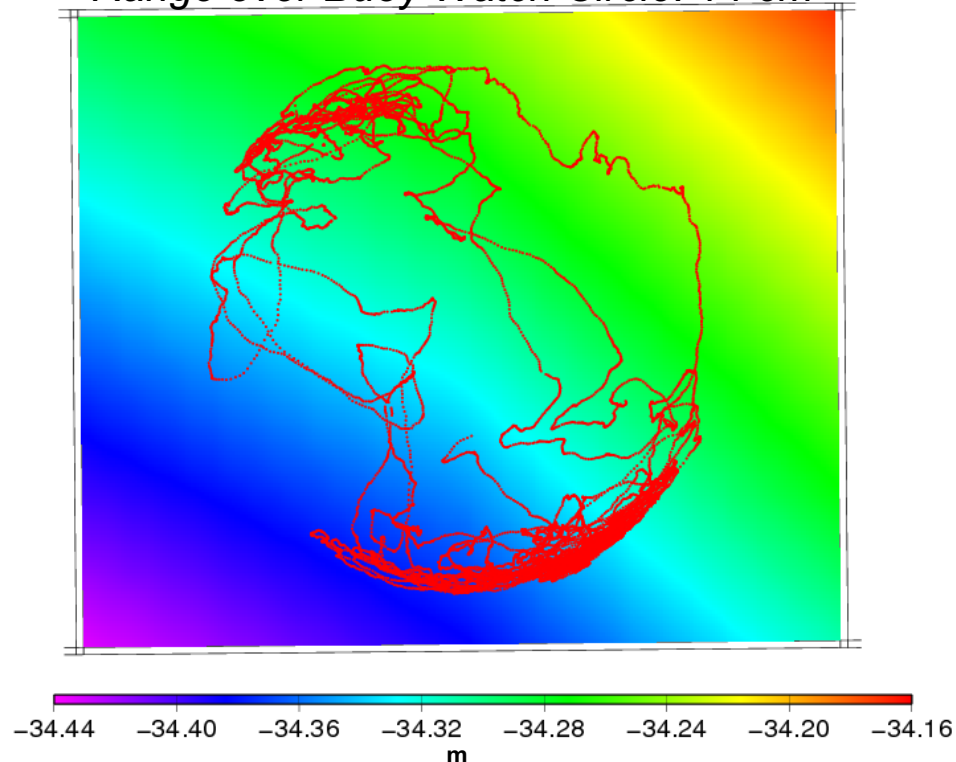
Range over Buoy Watch Circle: 530 m



Divins, D.L., and D. Metzger, NGDC Coastal Relief Model
<http://www.ngdc.noaa.gov/mgg/coastal/coastal.html>
<http://sccoos.org/data/bathy>

Geoid (from MSS Model)

Range over Buoy Watch Circle: 14 cm

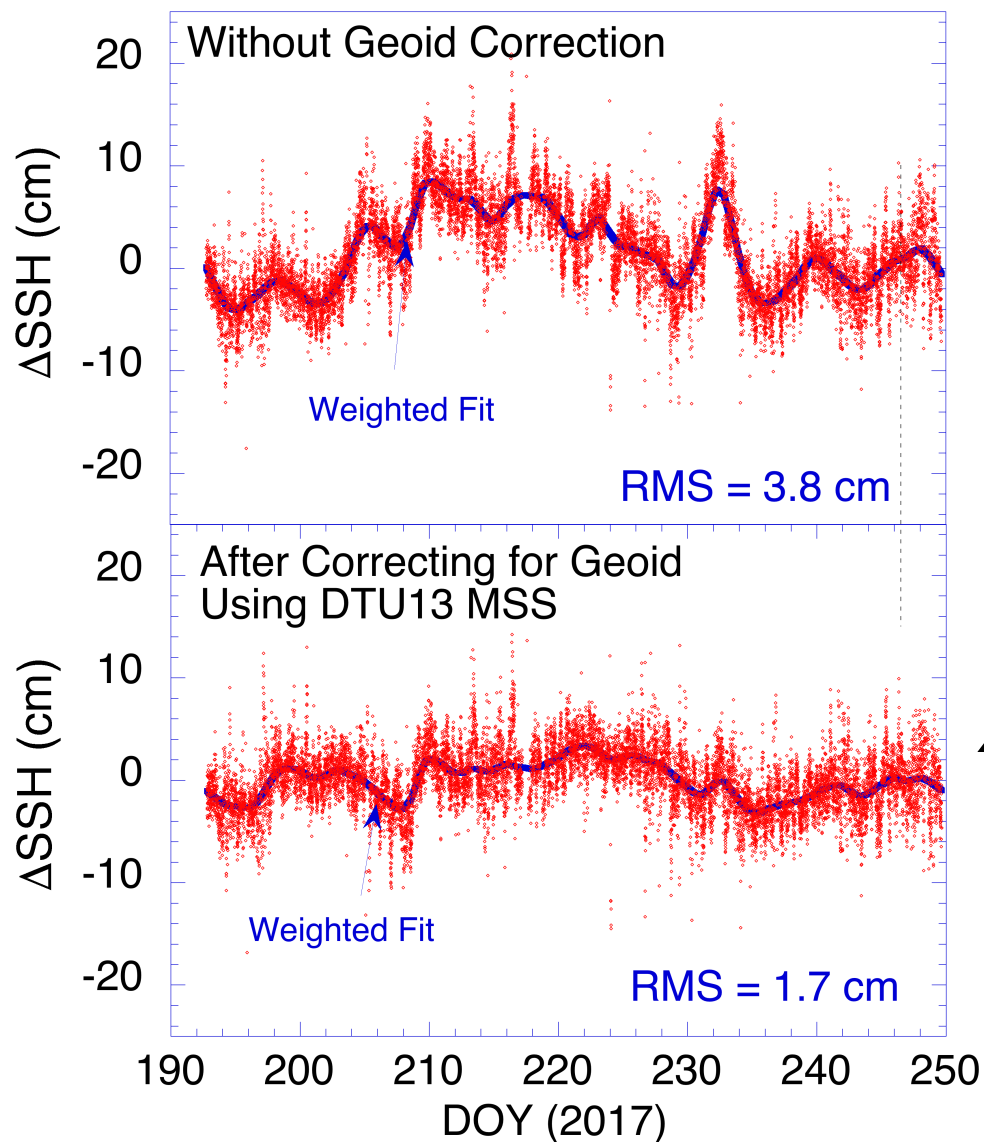


Andersen, O., P. Knudsen and L. Stenseng, The DTU13 MSS (Mean Sea Surface) and MDT (Mean Dynamic Topography) from 20 Years of Satellite Altimetry, IGFS 2014.



Monterey Buoy Results Underscore Importance of Geoid Signal

Strong Geoid Signal Observed in Time Series of GPS Buoy – Tide Gauge SSH



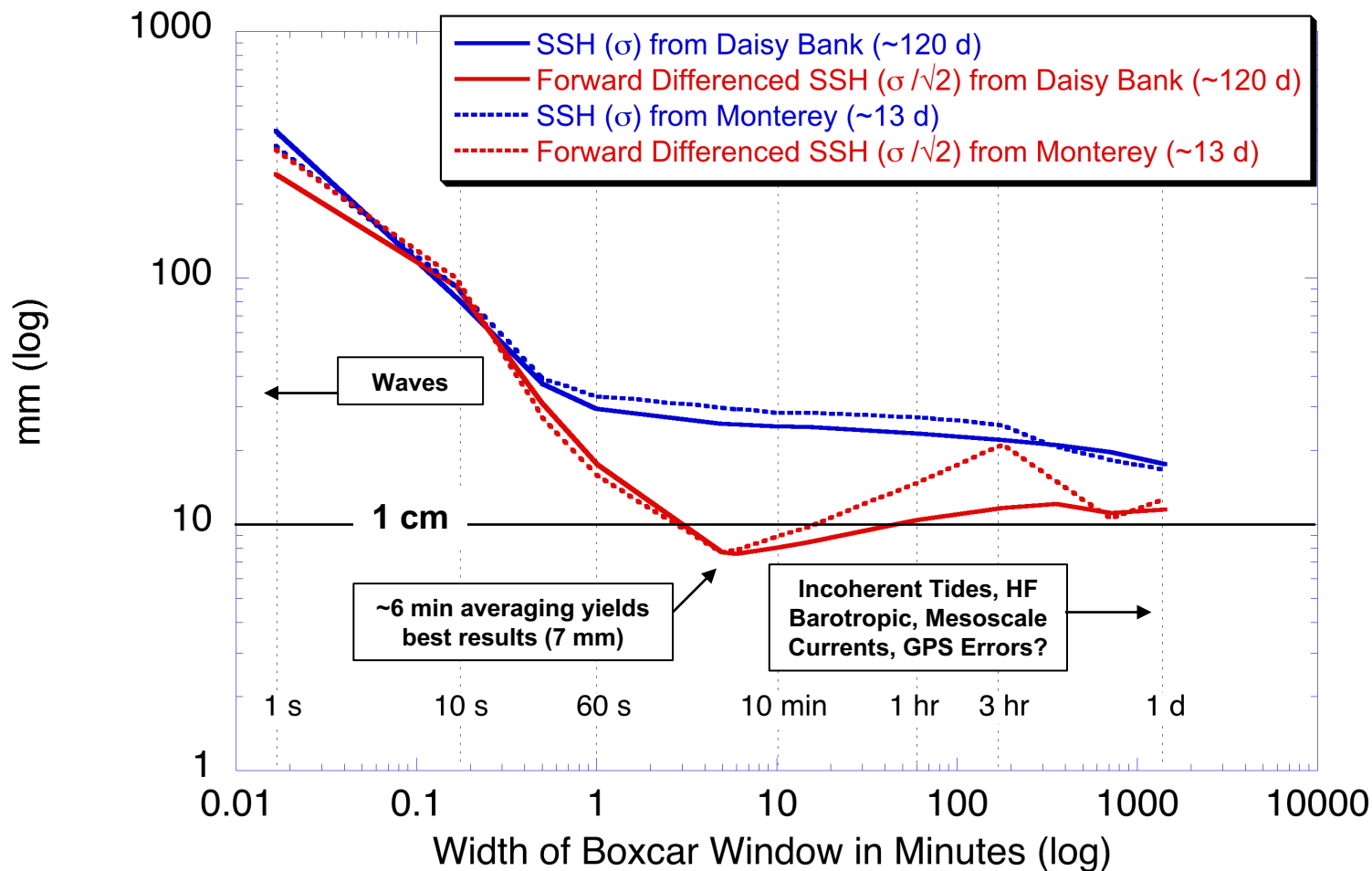
- In Monterey Experiment, buoy was moored in ~1000 m of water over the wall of Monterey Canyon.
- Significant small-scale geoid features observed as buoy traced out its path within 2-km (diameter) watch circle.
- Stationary, small (spatial) scale features in the geoid manifest as long (temporal) scale SSH anomalies, due to persistence of buoy in certain locations (driven by prevailing currents.)
- Simple correction from MSS (DTU13) captured anomalous signal observed in buoy vs. tide gauge differences.
 - Reduced variance of long-term SSH anomaly difference by 80%.
- Additional geoid signal remains, and could be measured using a dedicated GPS survey (Bonnetfond et al., 2003),



SSH Variability from GPS Buoy Data

Similar Results from Daisy Bank and Monterey Bay

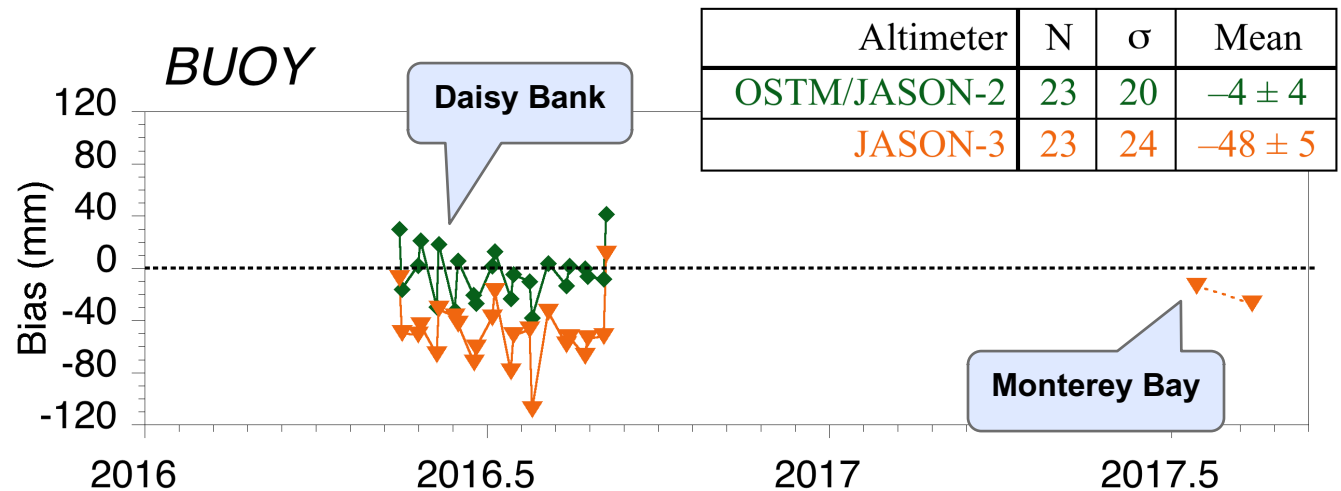
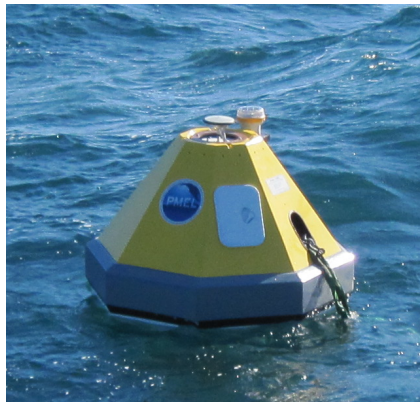
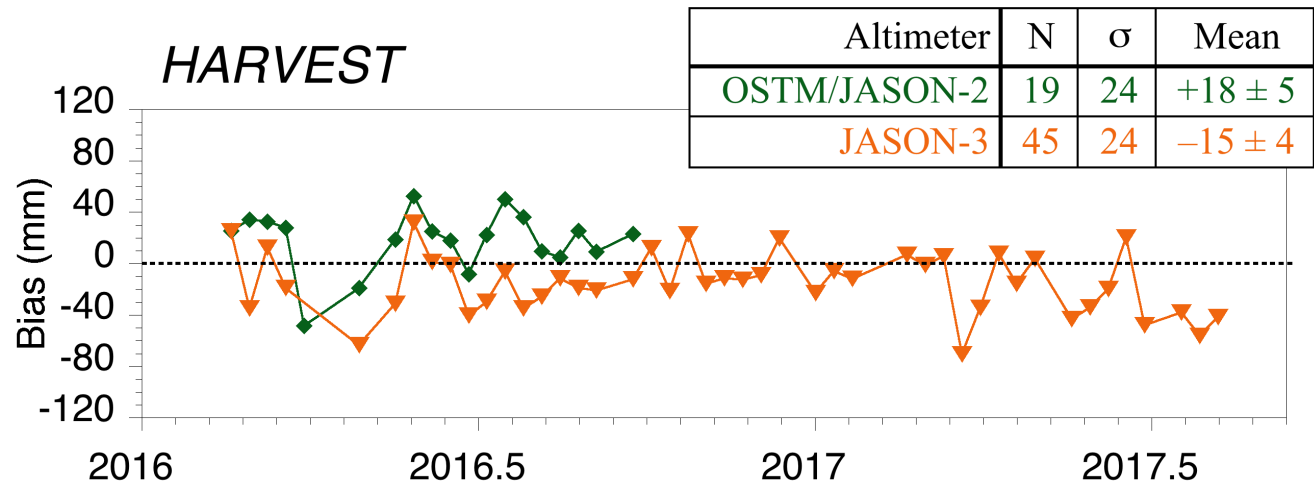
Buoy: SSH Variability vs. Width of Boxcar Window
(SSH corrected for tides and IB)





Verification of Altimeter Sea Surface Height: Harvest vs. Buoy (Daisy Bank + Monterey)

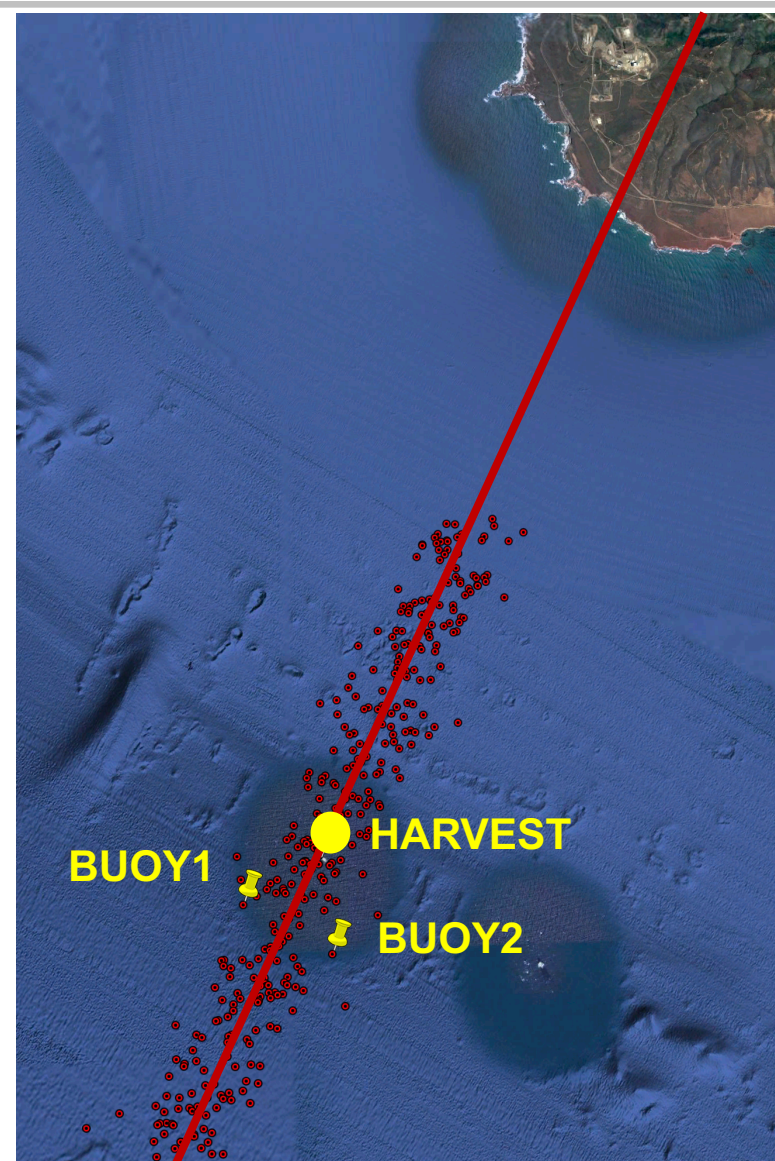
Comparable Results for the Jason-3 Era





Harvest Buoy Campaign: Aug. 2018 – Jan. 2019

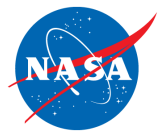
- Main goal: examine potential of precision GPS buoy systems to replace NASA Harvest verification site.
 - Risk reduction exercise for Jason-3 and Sentinel-6.
 - Anticipates possible platform loss or abandonment.
 - Buoys close to platform (~2 km) to support comparisons with platform tide gauges and overhead altimetry from Jason-3.
- Secondary goal: probe limits of GPS-based relative sea-surface height determination in open ocean.
 - Features two identically equipped surface buoys (new buoy modeled after prototype).
 - Buoys to be separated by ~2 km (TBC).
 - Short baseline will lend further insight on potential of GPS array for SWOT calval.
- Campaign enhancements
 - New longevity goal of 150 days: operate through higher (winter) sea states.
 - Buoys equipped with load cells to measure force on mooring (to study movement of buoy water line).
 - NOAA Prawler for taking TS measurements along mooring (TBC for one buoy).
 - Telemetry upgrade: 1-min snapshots of GPS tracking data to support basic positioning tests, and estimation of wet troposphere (1-Hz data saved onboard for recovery with buoys).





Summary

- **Preliminary results from GPS buoy very promising**
- **Comparisons with independent observations (altimetry and tide gauges) suggest precision of SSH estimates is close to 2 cm (hourly averages).**
- **Buoy competitive with Harvest for all altimeter calibration metrics**
- **Impact of waves less than 1 cm (for 1-Hz data with averaging windows > 5 min).**
- **Buoy also supports accurate retrievals of SWH, wet path delay and ionosphere.**
- **Upcoming Harvest Experiment to examine precision over short baseline in open ocean (relevant to performance of proposed SWOT GPS array).**



Backup Slides Follow

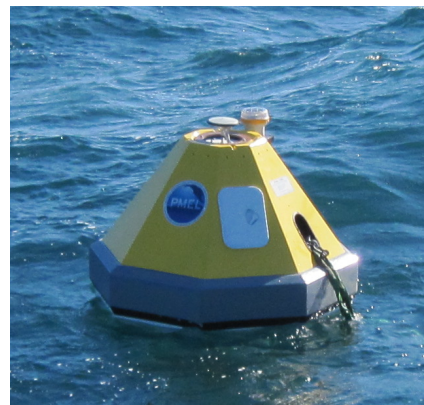
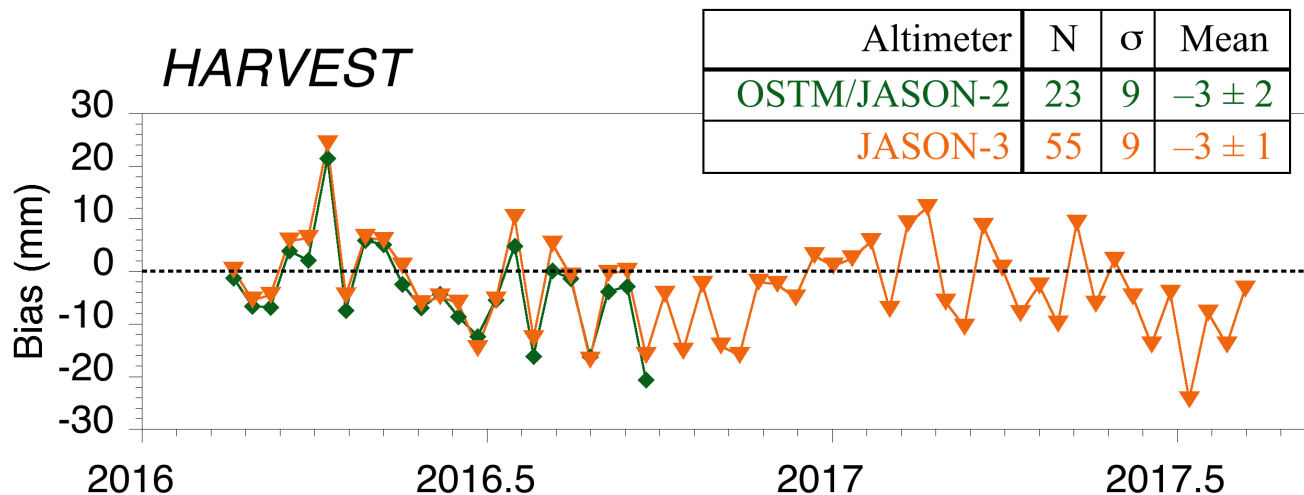


GPS Wet Path Delay Calibration: Harvest vs. Buoy

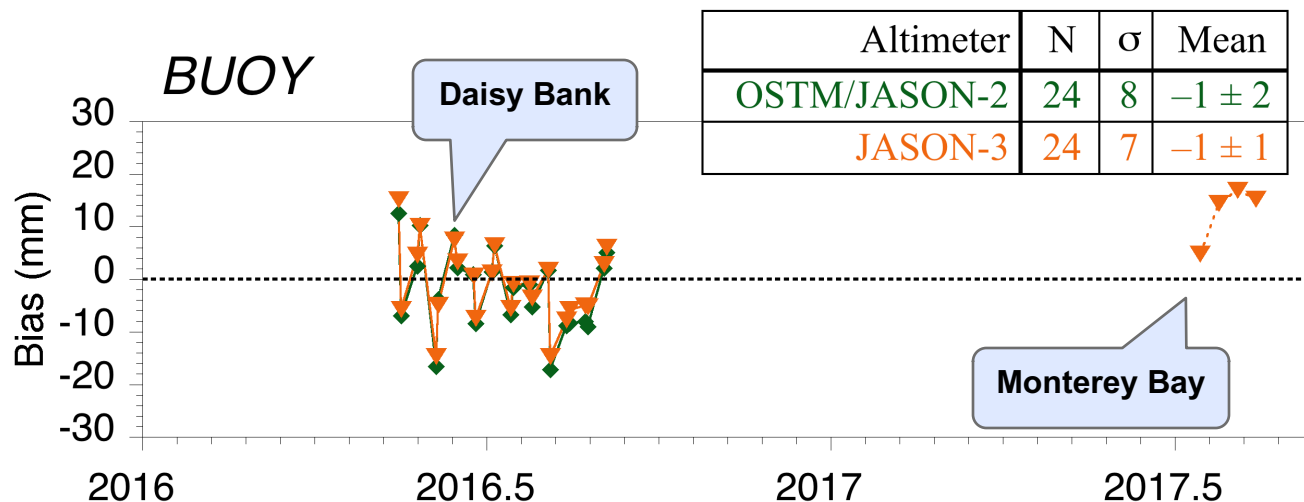
Comparable Results for the Jason-3 Era



HARVEST



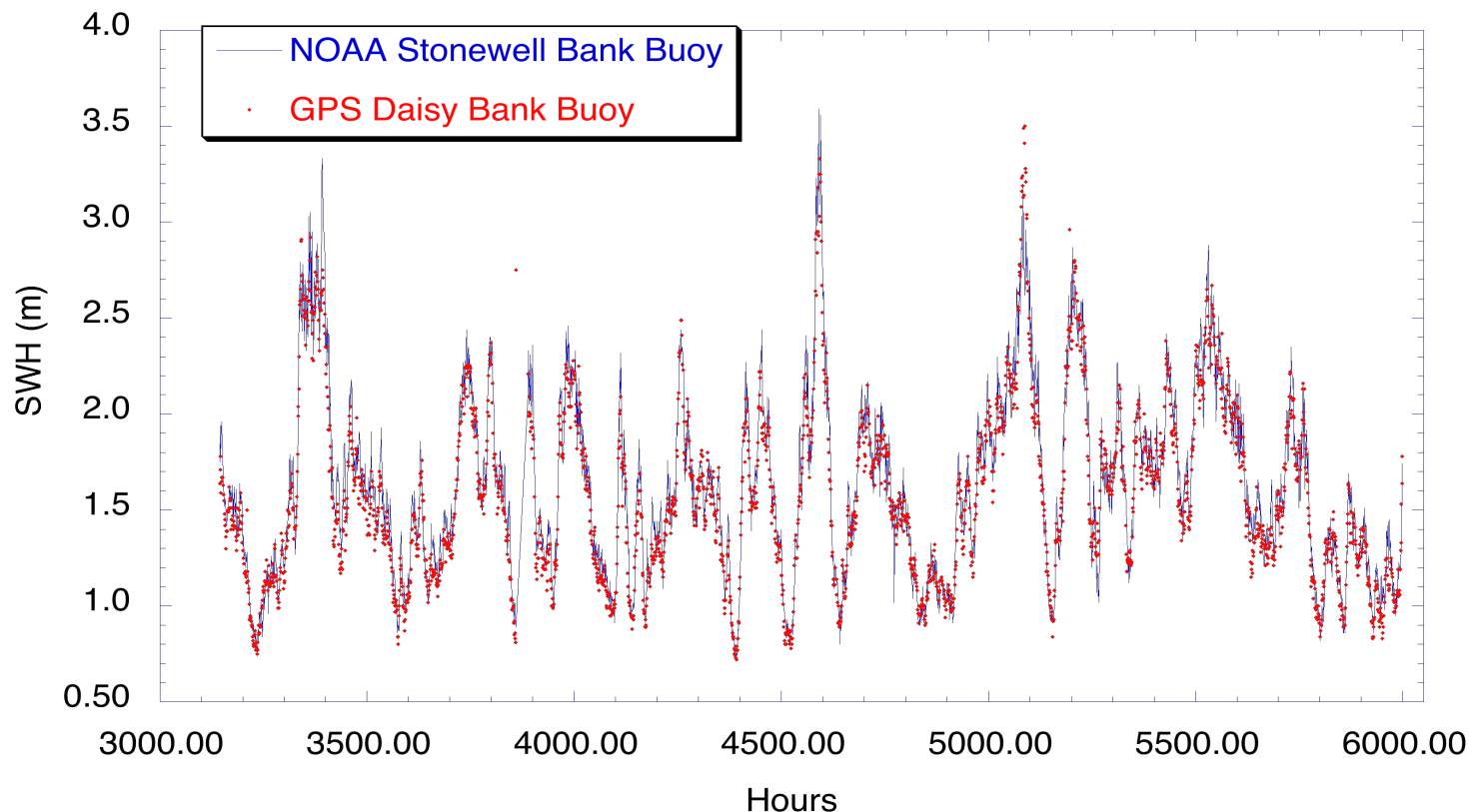
BUOY





Significant Wave Height Comparisons:

GPS Daisy Bank Buoy vs. NOAA Stonewall Bank Buoy (3-m discus)



- Precise 1-Hz GPS solutions enable dense sampling and characterization of waves (typical periods of 5–15 s).
- GPS solutions for SWH agree with traditional (accelerometer-based) buoy measurements at the 10–20 cm level.
- Appropriate filtering of high-rate GPS height estimates allows simultaneous and accurate recovery of SWH and mean SSH, both of which are relevant to SWOT.



GPS Buoy – Tide Gauge at Monterey Bay

Possible Signs of Incoherent Internal Tides

GPS — Tide Gauge at Monterey Bay:

EVALUATED OVER PERIOD REPRESENTED BY 900-m GLIDER DH

